Finite bias visibility of the electronic Mach-Zehnder interferometer

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We present an original statistical method to measure the visibility of interferences in an electronic Mach-Zehnder interferometer in the presence of low frequency fluctuations. The visibility presents a single side lobe structure shown to result from a gaussian phase averaging whose variance is quadratic with the bias. To reinforce our approach and validate our statistical method, the same experiment is also realized with a stable sample. It exhibits the same visibility behavior as the fluctuating one, indicating the intrinsic character of finite bias phase averaging. In both samples, the dilution of the impinging current reduces the variance of the gaussian distribution.

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Nowadays quantum conductors can be used to perform experiments usually done in optics, where electron beams replace photon beams. A beamlike electron motion can be obtained in the Integer Quantum Hall Effect (IQHE) regime using a high mobility two dimensional electron gas in a high magnetic field at low temperature. In the IQHE regime, one-dimensional gapless excitation modes form, which correspond to electrons drifting along the edge of the sample. The number of these so-called edge channels corresponds to the number of filled Landau levels in the bulk. The chirality of the excitations yields long collision times between quasi-particles, making edge states very suitable for quantum interferences experiments like the electronic Mach-Zehnder interferometer (MZI) [1, 2, 3]. Surprisingly, despite some experiments which show that equilibrium length in chiral wires is rather long [4], very little is known about the coherence length or the phase averaging in these "perfect" chiral uni-dimensional wires. In particular, while in the very first interference MZI experiment the interference visibility showed a monotonic decrease with voltage bias, which was attributed to phase noise [1], in a more recent paper, a surprising non-monotonic decrease with a lobe structure was observed [5]. A satisfactory explanation has not yet been found, and the experiment has so far not been reported by other groups to confirm these results.

We report here on an original method to measure the visibility of interferences in a MZI, when low frequency phase fluctuations prevent direct observation of the periodic interference pattern obtained by changing the magnetic flux through the MZI. We studied the visibility at finite energy and observed a single side lobe structure, which can be explained by a gaussian phase averaging whose variance is proportional to V^2, where V is the bias voltage. To reinforce our result and check if low frequency fluctuation may be responsible for that behavior, we realized the same experiment on a stable sample : we also observed a single side lobe structure which can be fitted with our approach of gaussian phase averaging. This proves the validity of the results, which cannot be an artefact due to the low frequency phase fluctuations in the first sample. In both samples, the dilution of the impinging current has an unexpected effect : it decreases the variance of the gaussian distribution.

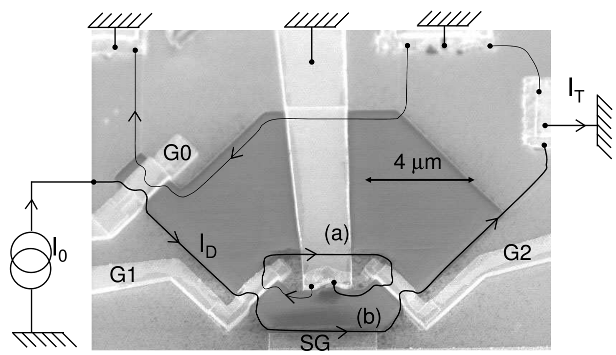

FIG. 1: SEM view of the electronic Mach-Zehnder with a schematic representation of the edge state. G0, G1, G2 are quantum point contacts which mimic beam splitters. The pairs of split gates defining a QPC are electrically connected via a Au metallic bridge deposited on an insolator (SU8). G0 allows a dilution of the impinging current, G1 and G2 are the two beam splitters of the Mach-Zehnder interferometer. SG is a side gate which allows a variation of the length of the lower path (b).

The MZI geometry is patterned using e-beam lithography on a high mobility two dimensional electron gas in a GaAs/Ga$_{1-x}$Al$_x$As heterojunction with a sheet density $n_S = 2.0\times10^{11}$ cm^{-2} and a mobility of 2.5×10^6 cm^2/Vs.

The experiment was performed in the IQHE regime at filling factor $\nu = n_S h/eB = 2$ (magnetic field B =5.2 Tesla). Transport occurs through two edge states with an extremely large energy redistribution length [4]. Quantum point contacts (QPC) controlled by gates G0, G1 and G2 define electronic beam splitters with transmissions $\mathcal{T}_0$, $\mathcal{T}_1$ and $\mathcal{T}_2$ respectively. In all the results presented here, the interferences were studied on the outer edge state schematically drawn as black lines in Fig.(1), the inner edge state being fully reflected by all the QPCs. The interferometer consists of G1, G2 and the small central ohmic contact in between the two arms. G1 splits the incident beam into two trajectories (a) and (b), which are recombined with G2 leading to interferences. The two arms defined by the mesa are 8 μm long and enclose a 14 μm^2 area. The current which is not transmitted through the MZI, $I_B = I_D - I_T$, is collected to the ground with the small ohmic contact. An additional gate SG allows a change of the length of the trajectory (b). The impinging current I_0 can be diluted thanks to the beam splitter G0 whose transmission $\mathcal{T}_0$ determines the diluted current $dI_D = \mathcal{T}_0 \times dI_0$. We measure the differential transmission through the MZI by standard lock-in techniques using a 619 Hz frequency 5 μV$_{rms}$ AC bias V_{AC} superimposed to the DC voltage V. This AC bias modulates the incoming current $dI_D = \mathcal{T}_0 \times h/e^2 \times V_{AC}$, and thus the transmitted current in an energy range close to eV, giving the transmission $\mathcal{T}(eV) = dI_T/dI_0$.

Using the single particle approach of the Landauer-Büttiker formalism, the transmission amplitude t through the MZI is the sum of the two complex transmission amplitudes corresponding to paths (a) and (b) of the interferometer; $t = t_0\{t_1 \exp(i\phi_a)t_2 - r_1 \exp(i\phi_b) r_2\}$. This leads to a transmission probability $\mathcal{T}(\epsilon) = \mathcal{T}_0\{\mathcal{T}_1\mathcal{T}_2 + \mathcal{R}_1\mathcal{R}_2 + \sqrt{\mathcal{T}_1\mathcal{R}_2\mathcal{R}_1\mathcal{T}_2}\sin[\varphi(\epsilon)]\}$, where $\varphi(\epsilon) = \phi_a - \phi_b$ and $\mathcal{T}_i = |t_i|^2 = 1 - \mathcal{R}_i$. $\varphi(\epsilon)$ corresponds to the total Aharonov-Bohm (AB) flux across the surface $S(\epsilon)$ defined by the arms of the MZI, $\varphi(\epsilon) = 2\pi S(\epsilon) \times eB/h$. The surface S depends on the energy ϵ when there is a finite length difference $\Delta L = L_a - L_b$ between the two arms. This leads to a variation of the phase with the energy, $\varphi(\epsilon + E_F) = \varphi(E_F) + \epsilon\Delta L/(\hbar v_D)$, where v_D is the drift velocity. When varying the AB flux, the interferences manifest themselves as oscillations of the transmission; in practice this is done either by varying the magnetic field or by varying the surface of the MZI with a side gate [1, 5, 6]. The visibility of the interferences defined as $\mathcal{V} = (\mathcal{T}_{MAX} - \mathcal{T}_{MIN})/(\mathcal{T}_{MAX} + \mathcal{T}_{MIN})$, is maximum when both beam splitter transmission are set to 1/2. In the present experiment the MZI is designed with equal arm lengths ($\Delta L = 0$) and the visibility is not expected to be sensitive to the coherence length of the source $\hbar v_D / max(k_B T, eV_{AC})$. Thus the visibility provides a direct measurement of the decoherence and/or phase averaging in this quantum circuit.

In Ref.[1], 60% visibility was observed at low temperature, showing that the quantum coherence length can be at least as large as several micrometer at 20 mK (and probably larger if phase averaging is the limiting factor). At finite energy (compared to the Fermi energy), the visibility was also found decreasing with the bias voltage[1, 5, 6]. This effect is not due to an increase of the coherence length of the electron source which remains determined by eV_{AC} or $k_B T$ [7]. In a first experiment, a monotonic visibility decrease was found, which was attributed to phase averaging, as confirmed by shot noise measurements [1]. Nevertheless, it remains unclear why and how the phase averaging increases with the bias. In a recent paper, instead of a monotonic decrease of the visibility, a lobe structure was observed for filling factor less than 1 in the QPCs [5]. No non-interacting electron model was found to be able to explain this observation, and although interaction effects have been proposed [8], a satisfactory explanation has not yet been found to account for all the experimental observations. So far, two experiments have shown to two different behaviors, raising questions about the universality of these observations. Here, we report experiments where different samples give consistent results, with a fit to the data clearly demonstrating that our MZI suffers from a gaussian phase averaging whose variance is proportional to V^2, leading to

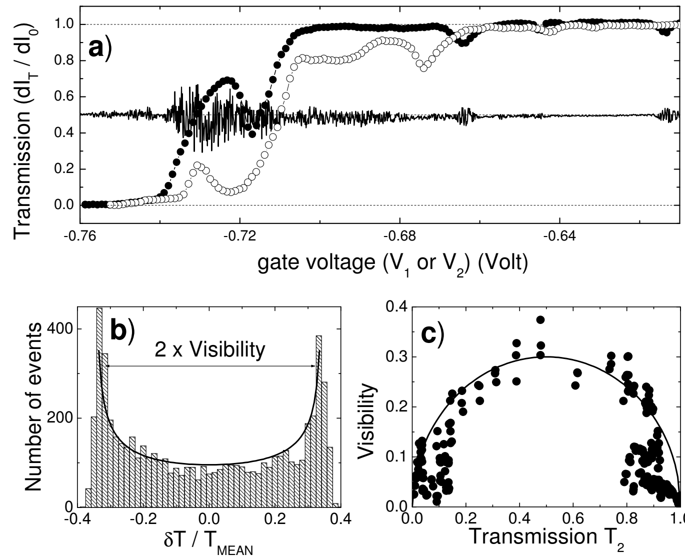

FIG. 2: **Sample #1 a)**Transmission $\mathcal{T} = dI_T/dI_0$ as a function of the gate voltages $V1$ and $V2$ applied on G1 and G2. (∘) $\mathcal{T} = \mathcal{T}_1$ versus $V1$. (•) $\mathcal{T} = \mathcal{T}_2$ versus $V2$. The solid line is the transmission $\mathcal{T}$ obtained with $\mathcal{T}_1$ fixed to 1/2 while sweeping $V2$: transmission fluctuations due to interferences with low frequency phase noise appears. **b)** Stack histogram on 6000 successive transmission measurements as a function of the normalized deviation from the mean value. The solid line is the distribution of transmission expected for a uniform distribution of phases. **c)**Visibility of interferences as a function of the transmission $\mathcal{T}_2$ when $\mathcal{T}_1 = 1/2$. The solid line is the $\sqrt{\mathcal{T}_2(1-\mathcal{T}_2)}$ dependence predicted by the theory.

the single side lobe structure of the visibility.

We have used the following procedure to tune the MZI. We first measure independently the two beam splitters' transparencies versus their respective gate voltages, the inner edge state being fully reflected. This is shown in figure (2**a**) where the transmission ($\mathcal{T}_1$ or $\mathcal{T}_2$) through one QPC is varied while keeping unit transparency for the other QPC. This provides the characterization of the transparency of each beam splitter as a function of its gate voltage. The fact that the transmission vanishes for large negative voltages means that the small ohmic contact in between the two arms can absorb all incoming electrons, otherwise the transmission would tend to a finite value. This is very important in order to avoid any spurious effect in the interference pattern. In a second step we fix the transmission $\mathcal{T}_1$ to 1/2 while sweeping the gate voltage of G2 (solid line of figure (2**a**)). Whereas for a fully incoherent system the $\mathcal{T}$ should be $1/2 \times (\mathcal{R}_2 + \mathcal{T}_2) = 1/2$, we observe large temporal transmission fluctuations around 1/2. We show in the following that they result from the interferences, expected in the coherent regime, but in presence of large low frequency phase noise. This is revealed by the probability distribution of the transmissions obtained when making a large number of transmission measurements for the same gate voltage. Figure (2**b**) shows a histogram of $\mathcal{T}$ when making 6000 measurements (each measurement being separated from the next by 10 ms). The histogram of the transmission fluctuations $\delta\mathcal{T} = \mathcal{T} - \mathcal{T}_{mean}$ displays two maxima very well fitted using a probability distribution $p(\delta\mathcal{T}/\mathcal{T}_{mean}) = 1/(2\pi\sqrt{1-(\delta\mathcal{T}/\mathcal{T}_{mean})^2/\mathcal{V}^2})$ (the solid line of figure (2**b**)). This distribution is obtained assuming interferences $\delta\mathcal{T} = \mathcal{T}_{mean} \times \mathcal{V} sin(\varphi)$ and a uniform probability distribution of φ over $[-\pi, +\pi]$. Note that the peaks around $|\delta\mathcal{T}/\mathcal{T}_{mean}| = \mathcal{V}$ have a finite width. They correspond to the gaussian distribution associated with the detection noise which has to be convoluted with the previous distribution.

Although no regular oscillations of transmission can be observed due to phase noise, we can directly extract the visibility of the interferences by calculating the variance of the fluctuations (the approach is similar to measurements of Universal Conductance Fluctuations via the amplitude of 1/f noise in diffusive metallic wires) [10]. As expected when $\mathcal{T}_1 = 1/2$, the visibility extracted by our method is proportional to $\sqrt{\mathcal{T}_2(1-\mathcal{T}_2)}$, definitively showing that fluctuations results from interference: we are able to measure the visibility of fluctuating interferences (see figure (2**c**)).

The visibility depends on the bias voltage with a lobe structure shown in figure (3), confirming the pioneering observation [5]. Nevertheless, there are marked differences. The visibility shape is not the same as that in ref.[5]. We have always seen only one side lobe, although the sensitivity of our measurements would be high enough to observe a second one if it existed. Moreover,

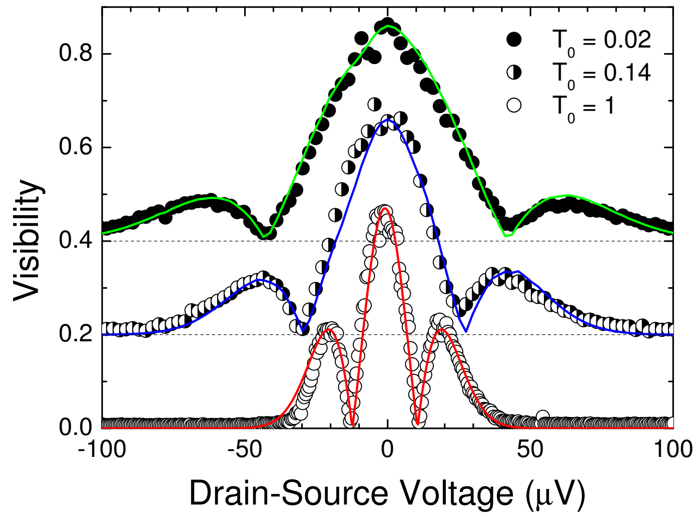

FIG. 3: (Color online) **Sample #1 :** Visibility of the interferences as a function of the drain-source voltage $I_0 h/e^2$ for three different values of $\mathcal{T}_0$. The curves are shifted for clarity. The energy width of the lobe structure is modified by the dilution whereas the maximum visibility at zero bias is not modified. Solid lines are fits using equation (1). From top to bottom, $\mathcal{T}_0 = 0.02$ and $V_0 = 31$ μV, $\mathcal{T}_0 = 0.14$ and $V_0 = 22$ μV, $\mathcal{T}_0 = 1$ and $V_0 = 11.4$ μV.

the lobe width (see figure (3)) can be increased by diluting the impinging current with G0, whereas no such effect is seen for G1 and G2. This apparent increase of the energy scale cannot be attributed to the addition of a resistance in series with the MZI because G0 is close to the MZI, at a distance shorter than the coherence length.

An almost perfect fit for the whole range of $\mathcal{T}_0$ (dilution), is

$$\mathcal{V} = \mathcal{V}_0 e^{-V^2/2V_0^2} |1 - \frac{V I_D}{V_0^2 dI_D/dV}|, \tag{1}$$

where V_0 is a fitting parameter. Equation (1) is obtained when assuming a gaussian phase averaging with a variance $< \delta\varphi^2 >$ proportional to V^2 and a length difference ΔL small enough to neglect the energy dependence of the phase in the observed energy range $eV \ll \hbar v_D/\Delta L$. In such a case, the interfering part of the current $I_\sim$ is thus proportional to $I_D \sin(\varphi)$. The gaussian distribution of the phase leads to $I_\sim \propto I_D \sin(<\varphi>) e^{-<\delta\varphi^2>/2}$, where $<\varphi>$ is the mean value of the phase distribution. The measured interfering part of the transmission, $\mathcal{T}_\sim = h/e^2\, dI_\sim/dV$ gives a visibility corresponding to formula (1) when $<\delta\varphi^2> = V^2/V_0^2$. Such behavior gives a nul visibility accompanied with a π shift of the phase when $V I_D/(V_0^2 dI_D/dV) = 1$. When $\mathcal{T}_0 \sim 1$, I_D is proportional to V and the width of the central lobe is simply equal to $2V_0$. However in the most general case, dI_D/dV varies with V. One can see in figure (3) that the fit with Equation (1) is very good, definitively showing that the

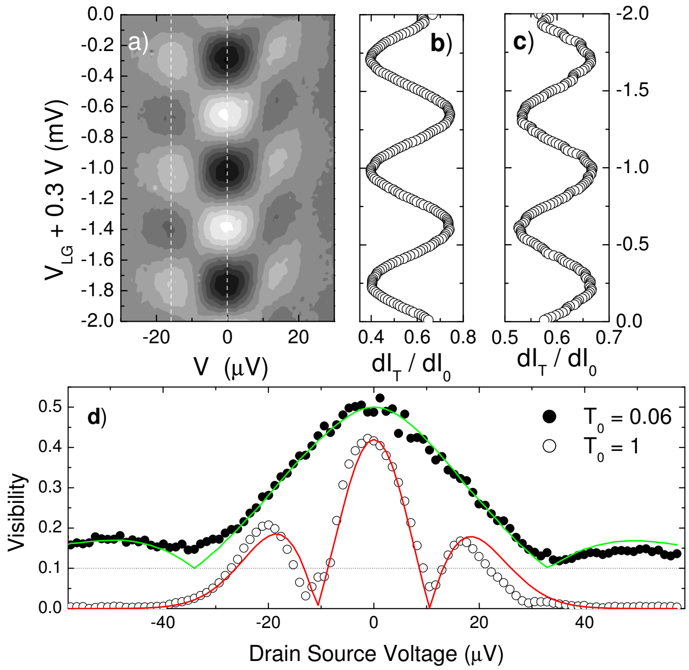

FIG. 4: (Color online) **Sample #2 : a)** Gray plot of the transmission $\mathcal{T}$ as a function of the bias voltage V and the side gate voltage V_{SG}. Note the π shift of the phase when the visibility reaches 0. **b) & c)** $\mathcal{T}$ as a function of the side gate voltage for two different values of the drain source voltage corresponding to the dashed line of **a)** (0 and 16 μV respectively). **d)** Lobe structure of the visibility fitted using equation (1) for a diluted and an undiluted impinging current.

existence of one side lobe, as observed in the experiment of ref.[5] at $\nu = 2$ (for the highest fields) and at $\nu = 1$, can be explained within our simple approach. Concerning multiple side lobes, we cannot yet conclude if they do arise from long range interaction as recently proposed by ref.[8]. Our geometry is different from the one used in the earlier experiment [5] and the coupling between counter propagating edge states, thought to be responsible for multiple side lobe [8], should be less efficient here.

To check if low frequency fluctuations have an impact on the finite bias phase averaging, we have studied another sample, with the same geometry and fabricated simultaneously (sample #2), which exhibits clear interference pattern (see Figure (4**a,b,c**)). As one can remark on figure (4**d**), the lobe structure is well fitted with our theory, definitively showing that the gaussian phase averaging is not associated with low frequency phase fluctuations.

It is noteworthy that V_0 increases (see figure (5)) with the dilution, namely when the transmission $\mathcal{T}_0$ at zero bias decreases. An impact of the dilution was already observed as it suppressed multiple side lobes [9] (arXiv version of Ref.[5]), but the conclusion was that the width of the central lobe was barely affected. Here, dilution plays a clear role whose $\mathcal{T}_0$ dependence is the same for the two studied samples, once normalized to the not diluted case. This dilution effect is nevertheless not easy to explain. For example, mechanisms like screening, intra edge scattering and fluctuations mediated by shot noise should have maximum effect at half transmission, in contradiction with figure (5). More generally, it is difficult to determine if the process responsible for the phase averaging introduced in our model is located at the beam splitters, or is uniformly distributed along the interfering channels. However, setting $\mathcal{T}_1 = 0.02$ or 0.05, keeping $\mathcal{T}_2 = 0.5$, leaves the lobe width unaffected. This shows that, if located at the Quantum Point Contacts, the phase averaging process is independent of transmission.

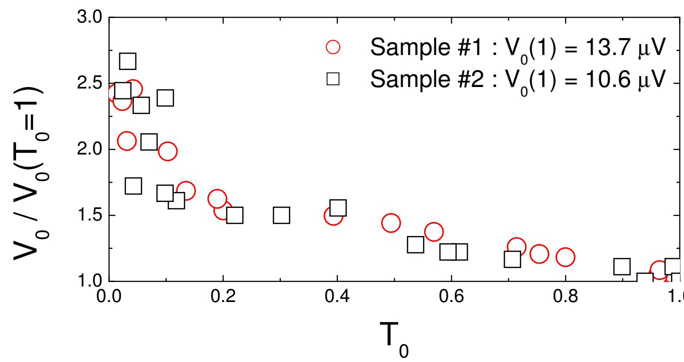

FIG. 5: (Color online) V_0 obtained by fitting the visibility with equation (1), normalized to V_0 at $\mathcal{T}_0 = 1$, as a function of $\mathcal{T}_0$ at zero bias.

To summarize, we propose a statistical method to measure the visibility of "invisible" interferences. We observe a single side lobe structure of the visibility on stable and unstable samples which is shown to result from a gaussian phase averaging whose variance is proportional to V^2. Moreover, this variance is shown to be reduced by diluting the impinging current. However, the mechanism responsible for such type of phase averaging remains yet unexplained.

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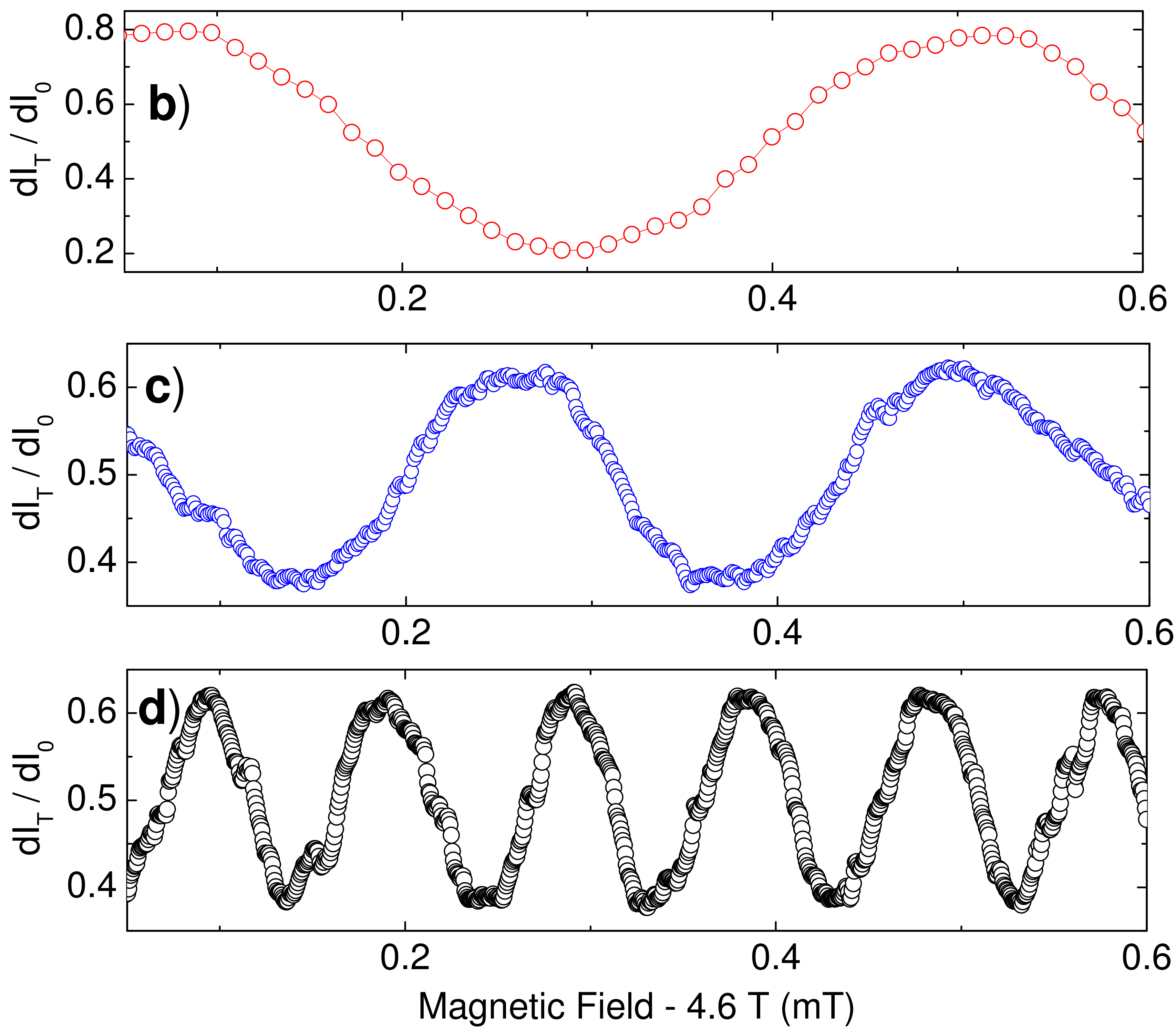
[10] All the results on the visibility reported here on sample #1 have been obtained using the following procedure : we measured $N = 2000$ times the transmission and calculated the mean value $\mathcal{T}_{mean}$ and the variance $< \delta\mathcal{T}^2 >$. It is straightforward to show that the visibility is $\mathcal{V} = \sqrt{2}\sqrt{< \delta\mathcal{T}^2 > - < \delta\mathcal{T}^2 >_0}/\mathcal{T}_{mean}$, where $< \delta\mathcal{T}^2 >_0$ is the measurement noise which depends on the AC bias amplitude, the noise of the amplifiers and the time constant of the lock-in amplifiers (fixed to 10 ms), measured in absence of the quantum interferences.



b)
c)
d)
dI_T / dI_0
0.2
0.4
0.6
0.8
0.5
Magnetic Field - 4.6 T (mT)